

# **INTENSITY REDISTRIBUTION FOR MILTICONJUGATE ADAPTIVE OPTICS (Postprint)**

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14. ABSTRACT MULTI-CONJUGATE ADAPTIVE-OPTICAL (MCAO) SYSTEMS HAVE BEEN PROPOSED AS A MEANS OF COMPENSATING BOTH INTENSITY AND PHASE ABERRATIONS IN A BEAM PROPAGATING THROUGH STRONG-SCINTILLATION ENVIRONMENTS. PROGRESS MADE ON IMPLEMENTING A MCAO SYSTEM AT THE STARFIRE OPTICAL RANGE (SOR), AIR FORCE RESEARCH LABORATORY, KIRTLAND AFB, IS DISCUSSED. AS A PRELIMINARY STEP TOWARD CONTROLLING A TWO DEFORMABLE MIRROR (DM) SYSTEM, THE FIRST-STAGE INTENSITY REDISTRIBUTION EXPERIMENT (FIRE) EXAMINES ONE ASPECT OF AN MCAO SYSTEM- CONTROL AND COMPENSATION OF WAVEFRONT INTENSITY. TWO WAVEFRONT SENSORS (WFS) AND A SINGLE DM ARE EMPLOYED FOR THIS EXPERIMENT. ONE WFS IS PLACED CONJUGATE TO THE DM WHILE THE SECOND WFS IS LOCATED AT A DISTANCE WHICH PRODUCES A DESIRED FRESNEL NUMBER FOR THE PROPAGATION BETWEEN THE WFSS. THE WFS MEASUREMENTS ARE INPUT TO A GERCHBERG-SAXTON BASED CONTROL ALGORITHM IN ORDER TO DETERMINE THE DM COMMANDS. THE PHASE PATTERN INTRODUCED BY THE DM IS CHOSEN SO PROPAGATION ALONG THE PATH BETWEEN THE TWO WFSS PRODUCES A DESIRED INTENSITY PROFILE AT THE SECOND WFS. THE SECOND WFS IS ALSO USED TO DETERMINE THE ACCURACY OF THE INTENSITY REDISTRIBUTION AND MEASURE ITS EFFECTS ON THE WAVEFRONT PHASE. IN THE NEXT PHASE OF MCAO DEVELOPMENT, A SECOND DM WILL BE ADDED CONJUGATE TO THE SECOND WFS IN ORDER TO CORRECT THE REMAINING PHASE ABERRATIONS. THE PAPER PRESENTS THE SETUP AND OPERATION FOR FIRE ALONG WITH INITIAL LABORTAROY RESULTS.					
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## Intensity redistribution for multiconjugate adaptive optics

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### ABSTRACT

Multi-Conjugate Adaptive-Optical (MCAO) systems have been proposed as a means of compensating both intensity and phase aberrations in a beam propagating through strong-scintillation environments. Progress made on implementing a MCAO system at the Starfire Optical Range, Air Force Research Laboratory, Kirtland AFB, is discussed. As a preliminary step toward controlling a two deformable mirror (DM) system, the First-stage Intensity Redistribution Experiment (FIRE) examines one aspect of an MCAO system—control and compensation of wavefront intensity. Two wavefront sensors (WFS) and a single DM are employed for this experiment. One WFS is placed conjugate to the DM while the second WFS is located at a distance which produces a desired Fresnel number for the propagation between the WFSs. The WFS measurements are input to a Gerchberg-Saxton based control algorithm in order to determine the DM commands. The phase pattern introduced by the DM is chosen so propagation along the path between the two WFSs produces a desired intensity profile at the second WFS. The second WFS is also used to determine the accuracy of the intensity redistribution and measure its effects on the wavefront phase. In the next phase of MCAO development, a second DM will be added conjugate to the second WFS in order to correct the remaining phase aberrations. This paper presents the setup and operation for FIRE along with initial laboratory results.

Keywords: amplitude reshaping, Gerchberg-Saxton algorithm, scintillation, multi-conjugate adaptive optics.

### 1. INTRODUCTION

The improved delivery of a high energy density beam at a predetermined distance through atmospheric turbulence is a proposed application for Multi-Conjugate Adaptive-Optical (MCAO) systems. Single deformable mirror (DM) adaptive optics (AO) systems typically correct phase aberrations and neglect scintillation effects. The results of analysis and simulation indicate that MCAO systems employ two DMs can control the deleterious effects of both phase aberrations and scintillation. Phase aberrations arise when collimated beams are projected through optical turbulence. Propagated a sufficient distance, these phase aberrations produce scintillation via constructive and destructive interference in the amplitude of the beam. MCAO control systems have been proposed that would mitigate these degradations, by performing full-wave conjugation, so that at a predetermined distance the spot size of a projected laser beam is as small as possible.<sup>1,2</sup> This goal can be achieved by dividing tasks, employing one DM for amplitude control and the secondary DM for phase control.

In this paper, lab results are presented for the First-Stage Intensity Redistribution Experiment (FIRE).<sup>3</sup> The goal of FIRE is to demonstrate and verify the amplitude control performance predicted by theory. The FIRE configuration consists of a single DM at what will be called the primary plane, a wavefront sensor (WFS) conjugate to the DM, and a WFS placed at a secondary plane at a distance that produces a specified Fresnel number. A FIRE control algorithm accepts a phase-aberrated and scintillated input beacon received from the target distance. The output of the FIRE algorithm are the phase distortions required to produce a desired amplitude pattern at the target distance as shown in Figure 1. If a full MCAO control system had been implemented, a second DM would have been employed for phase control at the secondary plane. Its task would be to conjugate the phase of the incoming beacon so that uniform phase is achieved.

The FIRE amplitude control system employs a Gerchberg-Saxton based algorithm constrained in three parameters.<sup>4</sup> FIRE algorithm phase solutions for both clean and scintillated input beams were produced for preselected intensity patterns. Then, amplitude control performance was evaluated in the laboratory by applying these solutions to the DM and taking recordings from the secondary WFS at the desired target range from the DM. An additional consideration is the resultant phase aberrations due to the phase

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distortions associated with amplitude reshaping. If the phase aberrations are too great, actuator throw of the secondary DM will be insufficient to conjugate the output beam to that of the beacon.

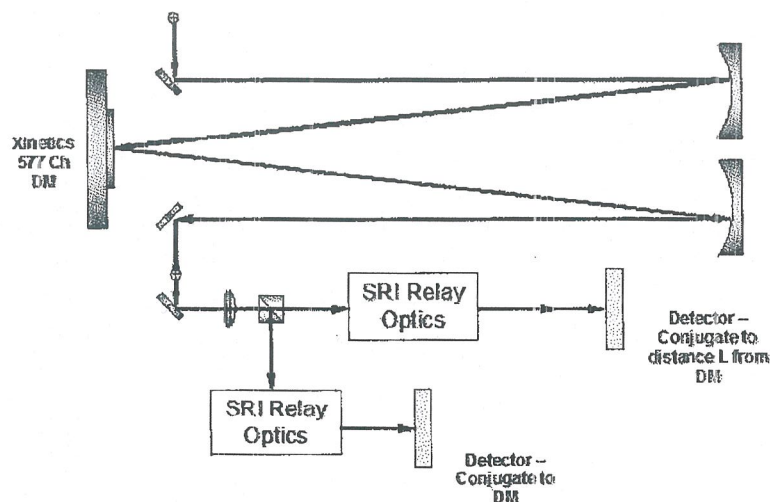


Figure 1. Phase distortions applied to the beam by the DM coupled with propagation produce the desired amplitude pattern at distance L. The pupil plane is called the primary plane in the text.

The outline of this paper is as follows: modeling and simulation are given in Section 2, laboratory experiments are described in Section 3, results are presented in Section 4, and concluding remarks are given in Section 5.

## 2. MODELING AND SIMULATION

A description of the FIRE algorithm and its expected amplitude control performance are presented in this section. The FIRE algorithm employs a Gerchberg-Saxton based phase retrieval algorithm as shown in Figure 2. The algorithm projects onto constraint sets in two planes separated by propagation over a distance, L, in the Fresnel region. Also, the distance L ensures that the beam is oversampled in the second WFS. Three constraints are enforced in the plane corresponding to the pupil plane of the system: an amplitude constraint, actuator resolution constraint, and a DM stroke limit. These constraints merit inclusion because they represent more accurately the physical limits of the optical system; this is the plane associated with the forward propagation direction. Since the reverse propagation direction does not contribute to the physics of the problem, we enforce only the desired amplitude constraint in the secondary plane.

The 27 x 27 poke array sized DM employed in this research was not be able to reproduce the phase contours demanded by an unconstrained solution that was produced using a 200 x 200 array. Thus, the resolution constraint was included in the Gerchberg-Saxton solution in the pupil plane of the system. The resolution constraint uses a cubic spline model of the actuator influence take into account the physical limitations on the slope of the phase between actuators in the DM. The equation modeling the DM pokes to the supersampled phase from the Gerchberg-Saxton solution is

$$\hat{\phi} = Hc, \quad (1)$$

where  $\phi$  is the supersampled phase, H is the influence matrix that enforces the resolution constraint and c is the vector of DM actuator commands. Solving for c produces the estimate

$$\hat{c} = (H^T H^{-1}) H^T \hat{\phi}. \quad (2)$$

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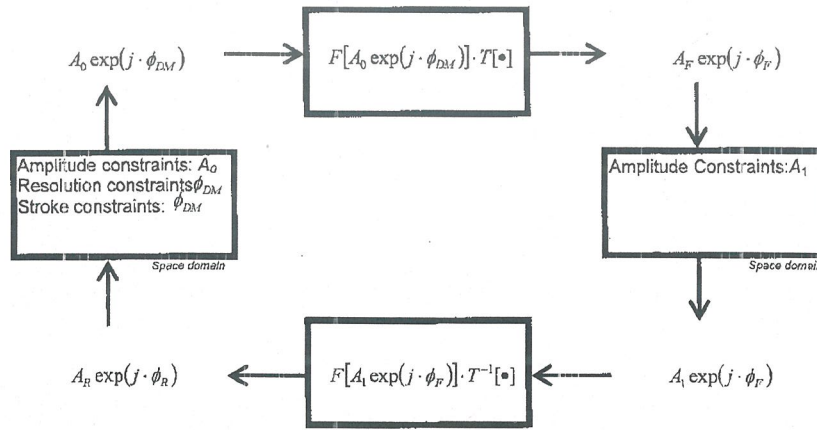


Figure 2. Block diagram of the FIRE control algorithm. Beam amplitude is reshaped by an iterative projection-on-constraints technique.

Because  $H$  is not full rank, the pseudoinverse of  $H$  is used. The resultant estimate  $\hat{c}$  is the least-squares estimate of the poke array required to recreate  $\phi_{DM}$  given the constraints enforced by  $H$ . Then, the constrained estimate  $\hat{c}$  is employed to produce a constrained phase for use by the Gerchberg-Saxton algorithm by

$$\phi_{DM} = H\hat{c}, \quad (3)$$

where  $\phi_{DM}$  is the phase produced by the command vector  $\hat{c}$ . The solution described above accounts for DM pokes that fall within the aperture. DM poke array elements that fall outside of the aperture were assigned values via weighted averaging of nearest neighbors. Also, an additional DM stroke constraint is enforced in the pupil plane. This constraint limited the range of actuator commands to what is physically available from the DM. Thus, DM throw is reserved for the range of poke values most demanded by the histogram of the FIRE algorithmic phase solution.

Performance of the FIRE algorithm was measured by use of the Strehl ratio. Amplitude Strehl ratios utilize the results obtained from simulation against ideal reshaped amplitudes. FIRE predicted amplitudes were evaluated against ideal desired amplitude shapes using an amplitude Strehl ratio as given by

$$S = \frac{\sum_{\mathbf{x}} |A_1(\mathbf{x}) A_2^*(\mathbf{x})|^2}{\sum_{\mathbf{x}} |A_1(\mathbf{x})|^2 \sum_{\mathbf{x}} |A_2^*(\mathbf{x})|^2}, \quad (4)$$

where  $A_1$  and  $A_2$  are the amplitudes being compared.

The FIRE algorithm was employed in simulations in order to evaluate its performance. The input beam was the actual measured intensity from the laser employed in this experiment. Its beam amplitude shape is similar a clipped-Gaussian. A uniform amplitude is assumed for the ideal amplitude for each preselected amplitude shape to be created in the secondary plane. The simulated results of forward propagation for an X shape are shown in Figure 3 and the amplitude Strehl ratios for simulated amplitudes versus ideal amplitudes are given in Table 1. The phase map solution from the FIRE algorithm, displayed in Figure 3(b), is applied to the DM to achieve the simulated amplitude reshaping of Figure 3(c). Figure 4 shows the reverse propagation direction that is employed only within the FIRE algorithm.

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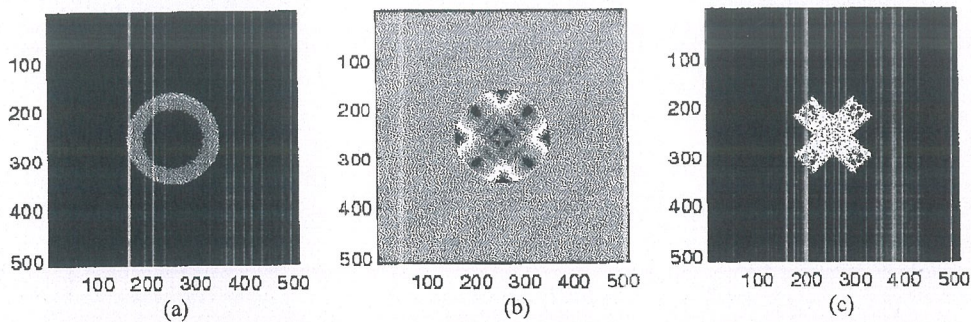


Figure 3. Forward propagation: (a) constrained amplitude  $A_0$ , (b) dual constrained phase  $\phi_{DM}$ , (c) resultant amplitude  $A_F$  in the secondary plane after propagating distance  $L$ .

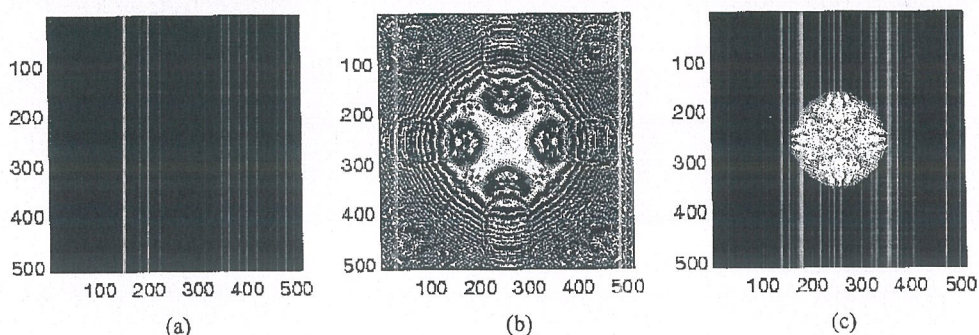


Figure 4. Reverse propagation: (a) constrained amplitude  $A_1$ , (b) unconstrained phase, (c) resultant amplitude in the primary plane after the propagating distance  $-L$ .

### 3. LABORATORY EXPERIMENT DESCRIPTION

The FIRE experiment was conducted in the SOR's Atmospheric Simulation and Adaptive-Optics Laboratory Testbed (ASALT). The ASALT Lab consists of the laboratory space, optics benches, hardware and computer support necessary to conduct AO experiments. Personal computers (PC) are networked in the ASALT Lab to form an overarching software control system that provides an integrated operating environment. One PC is assigned as the master controller. Additional PCs are assigned to software control tasks for subsystems. For example, PCs control DMs, Atmospheric Turbulence Simulators (ATS), cameras, and sensors. An ASALT Lab layout viewer resides in the master controller. Each software control package is represented as a drop-in object. Complete systems are formed by stringing together objects in the layout viewer.

The FIRE configuration is shown in Figure 5. A  $1.55\mu\text{m}$  wavelength laser provided the input beam for the system. The beam was expanded to fill the DM via an off-axis parabola (OAP). The second OAP redirects the beam back to its original dimensions. Then, the beam is split and optical elements are inserted in the path so that two pupils conjugate to the DM are formed. A self-referencing interferometric (SRI) wavefront sensor (WFS) is placed at the pupil of the DM.<sup>5</sup> Another SRI WFS, labeled the FIRE WFS, is placed in the right leg of the experimental configuration at a distance  $L$  corresponding to the desired Fresnel number.

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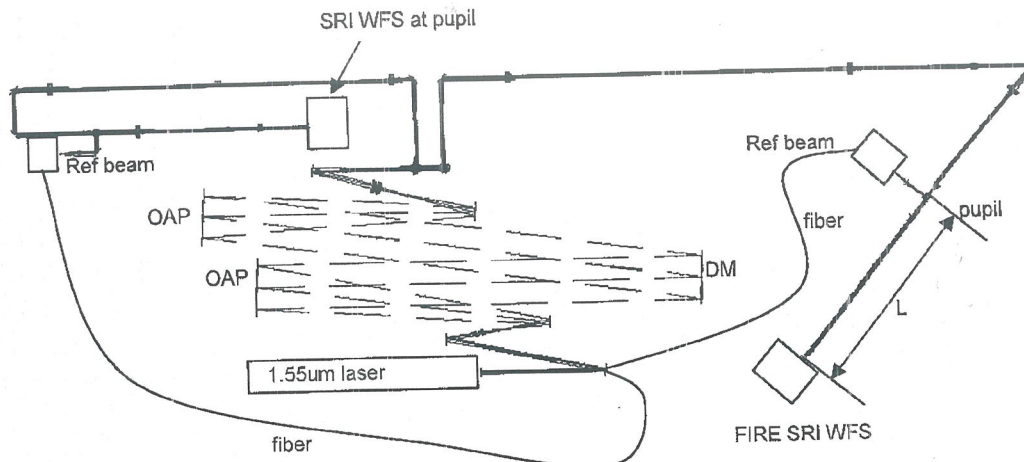


Figure 5. FIRE experimental configuration. Fiber relays insert a beam reference for the SRIs. The FIRE SRI WFS is located conjugate to a distance  $L$  from the DM.

The ASALT Lab control system was employed to conduct amplitude reshaping experiments using the FIRE algorithm. Integration of a closed loop system for driving the DM was completed with the ASALT Lab layout tool. The main feedback element within the closed loop system was the pupil WFS phase measurement. This measurement was compared with the desired DM phase, obtained from simulation, in order to drive the DM actuators. Then, intensity and phase measurements of the resultant reshaped signal beam were recorded in the secondary plane with the FIRE WFS. Consecutive intensity and phase measurements were taken by alternately blocking and unblocking the reference beams.

#### 4. RESULTS

As a first step toward a real-time implementation, the FIRE control algorithm was applied to static cases. The static case allowed time for FIRE to run to convergence before it was applied to the ASALT control system. Then, the resultant phase map was applied to the WFS at pupil and the control loop was closed between the WFS and the DM, as discussed in the previous section. In order to verify the basic operation of the FIRE algorithm, initial experiments employed an unaberrated laser beam input. The unaberrated input beam was produced with a  $1.55\mu\text{m}$  wavelength laser that outputs an approximately clipped-Gaussian amplitude beam profile. Then, the complexity of the lab task was increased by using the ASALT Lab Automatic Turbulence Simulator to produce a scintillated input beam. Results from both experiments are presented in this section. Although it would be useful as a feedback element, measurements from the FIRE WFS were used solely for evaluating amplitude reshaping and phase aberration performance.

Amplitude shaping results for the unaberrated beam input case are shown in Figure 6. Expected amplitudes from simulation assume use of a WFS with a  $200 \times 200$  poke array. Amplitude reshaping results from the laboratory employed a DM with a  $27 \times 27$  poke array. The shapes shown in Figure 6 have an assortment of rounded and straight edges and corners. Additionally, every shape was employed in three different sizes. This combination of beam shapes and sizes provided a basis for evaluation of the FIRE algorithm. The amplitude Strehl ratios for these shapes are shown in Table 1. A uniform amplitude is assumed to be the ideal amplitude for each shape. The amplitude Strehl ratio for the large rectangle shape was ranked highest. The rectangle shape taxed the DM least because of its shape was relatively smooth compared to the others shapes and its lack of interior features. Although the Strehl ratios were close, the darkened interior of the "O" shape was more difficult to reproduce than the square corners of the rectangle. It seems reasonable to conclude that the amount of Fourier domain high spatial frequency content accounts for the differences in the Strehl ratios. Simulations of a flat-top circularly shaped amplitude support this conclusion. Simulations showed that amplitude Strehl ratios of more than 0.98 are possible for this shape. Also, the medium and large shapes consistently produced much higher amplitude Strehl ratios than the

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small shape. Because the medium and large shapes had approximately the same width as the diameter of the input beam, the DM had to "push" light a relatively small distance in the transverse direction. In this laboratory setup, a tradeoff existed between spreading the available light too thinly with a large shape and pushing the light too far from the perimeter of the beam toward the center for small shapes. Figure 7 shows the amplitude results for three different sizes of the X shape. Additionally, the phase aberrations of the reshaped beams were checked for excessive phase variance. In all cases checked, phase conjugation would have been possible using the same DM employed for amplitude shaping. Figure 8 provides a visual comparison of reshaped amplitude and phase for the medium O shape. Figure 9 shows initial results for reshaping a scintillated beam into a circularly shaped flat-top amplitude beam.

Shape	Amplitude Strehl Ratios		
	<u>sim vs ideal</u>	<u>lab vs sim</u>	<u>lab vs ideal</u>
Triangle			
large	0.916	0.530	0.485
medium	0.925	0.444	0.410
small	0.918	0.349	0.321
Rectangle			
large	0.950	0.750	0.712
medium	0.968	0.603	0.589
small	0.907	0.350	0.317
O			
large	0.943	0.519	0.490
medium	0.939	0.439	0.412
small	0.898	0.299	0.268
X			
large	0.938	0.617	0.579
medium	0.922	0.513	0.473
small	0.911	0.321	0.292

Table 1. Amplitude Strehl ratios.

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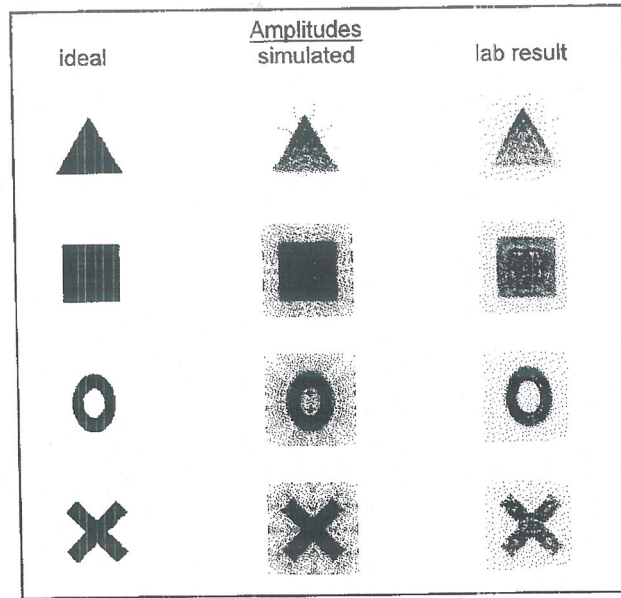


Figure 6. Simulation and lab results of amplitudes for the medium-sized preselected shapes.

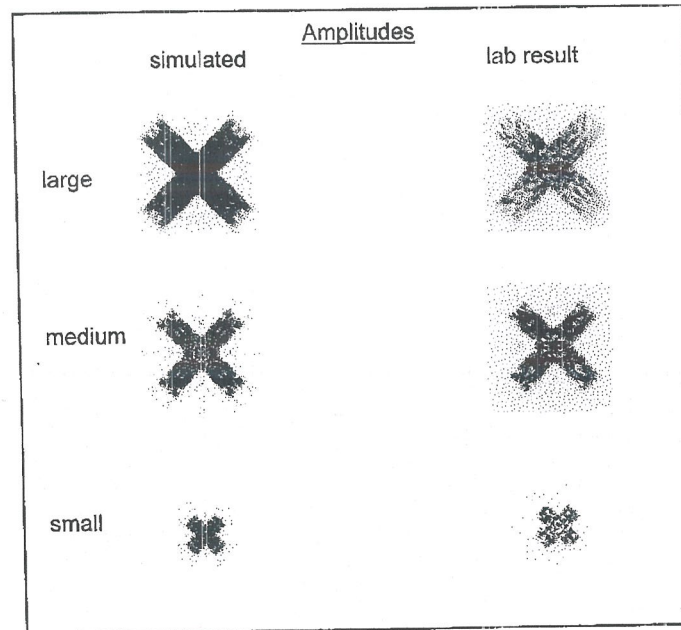


Figure 7. Each preselected amplitude shape was employed in three different sizes. The large size was approximately as broad as the diameter of the input beam.

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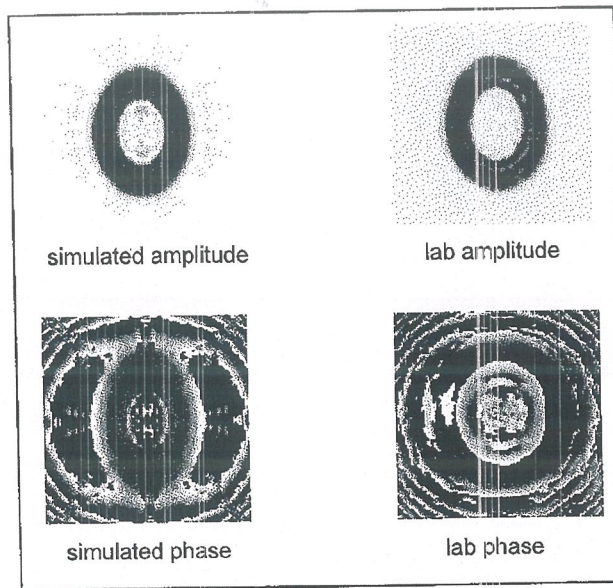


Figure 8. A visual comparison of amplitude and phase for the medium O shape.

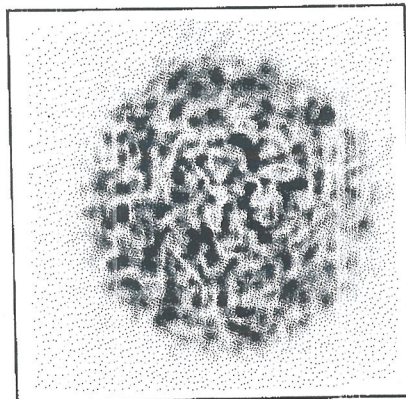


Figure 9. Initial results for reshaping a scintillated beam into a circularly shaped flat-top amplitude beam.

## 5. CONCLUDING REMARKS

FIRE was shown to be a dependable amplitude shaping control system. Strehl ratios of simulation versus ideal amplitudes provided the expected performance of the system with an  $200 \times 200$  poke array DM. Strehl ratios of laboratory versus simulation showed the performance of the FIRE control system when a coarse  $27 \times 27$  poke array DM was employed. Amplitude reshaping was found to be most efficient when the reshaped beam size is approximately the size of the input beam.

In future work, a reasonable goal would be to decrease algorithm compute time so that a real-time implementation of FIRE could be achieved. Several iterations are needed for convergence in the static case because the algorithm is iterating toward a fresh solution. Because the intensity differences between successive frames would probably be small, the computational expense in a real-time implementation of the FIRE algorithm could be lessened by seeding the algorithm with the previous phase solution. Also, the fiber relay reference leg for the SRI could be removed.

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